Superconducting Spintronics in the Presence of Spin-Orbital Coupling

Yury M. Shukrinov, Ilhom R. Rahmonov, and André E. Botha

***Abstract*—We study various physical phenomena in a φ_0 Josephson junction with a direct coupling between magnetic moment and Josephson current. We demonstrate three types of effects that lead to magnetization reversal in the ferromagnetic layer, including the magnetic moment reversal 1) by a pulse of superconducting current, 2) by a linearly decreasing bias voltage in the φ_0-junction, and 3) by a pulse of external magnetic field in an rf-SQUID with a φ_0-junction. The influence of the model parameters of the systems on magnetization reversal is investigated in detail. The observed features might find applications in different fields of superconducting spintronics.**

***Index Terms*—φ_0 junction, magnetization reversal, superconductor/ferromagnet/superconductor structures.**

I. Introduction

SPINTRONICS is one of the most intensively developing fields within condensed matter physics. An important place in this field is occupied by the investigations of Josephson junctions in combination with magnetic systems [1]. There exists a possibility to manipulate the magnetic properties via the Josephson current, and the opposite, i.e., to manipulate the Josephson current by a magnetic moment. This possibility has attracted much recent attention [2]–[4].

An important role in these phenomena is played by a spin-orbit interaction. In the superconductor/ferromagnet/supercond uctor (S/F/S) Josephson junctions, the spin-orbit interaction in a ferromagnet without inversion symmetry, provides a mechanism for a direct (linear) coupling between the magnetic moment and the superconducting current. In a noncentrosymmetric ferromagnetic junction, hereafter referred to as a φ_0-junction [5]–[8], the time reversal symmetry is broken, and the current-phase relation becomes $I_s = I_c \sin(\varphi - \varphi_0)$, where the phase shift φ_0, is proportional to the magnetic moment component perpendicular to the gradient of the asymmetric spin-orbit potential and to the parameter of spin orbit coupling. This relation allows manipulation of the internal magnetic moment via the Josephson current [5], [9].

Though the static properties of S/F/S structures are well studied, both theoretically and experimentally, much less is known about the magnetic dynamics of these systems. Only a few theoretical works exist in which the influence of the Josephson current on the magnetic system has been investigated [10]–[12]. In [9], the spin dynamics associated with such φ_0-junctions was studied theoretically. Konschelle and Buzdin considered a simple S/F/S φ_0-junction in a low frequency regime, which allowed them to use the quasi-static approach. It was demonstrated that a dc superconducting current might produce a strong orientation effect on the ferromagnetic layer magnetic moment. The application of a dc voltage on the φ_0-junction would produce current oscillations and consequently magnetic precession.

In this paper, we study the magnetization reversal in the φ_0-junction by three different methods, including, by applying a pulse of superconducting current and a linearly decreasing bias voltage. For the first time, the magnetization reversal by the pulse of the external magnetic field in an rf-SQUID with a φ_0-junction is investigated. We have explored the possibility of controllable magnetization reversal and carried out investigations of the magnetization dynamics, which allow us to demonstrate complete magnetization reversal in these systems. We found that complete magnetization reversal is very sensitive to the junction, ferromagnetic layer, and pulse parameters.

II. Model and Methods

In order to study the dynamics of the S/F/S system, we use the method developed in [9]. A schematic representation of the φ_0–junction is shown in Fig. 1. We assume that the gradient of the spin-orbit potential is along the easy axis of magnetization, taken to be along $\hat{z}$ axis. A pulse of superconducting current is directed along $\hat{x}$ axis.

The total energy of this system can then be written as

$$E_{\text{tot}} = -\frac{\Phi_0}{2\pi}\varphi I + E_s(\varphi, \varphi_0) + E_M(\varphi_0) \tag{1}$$

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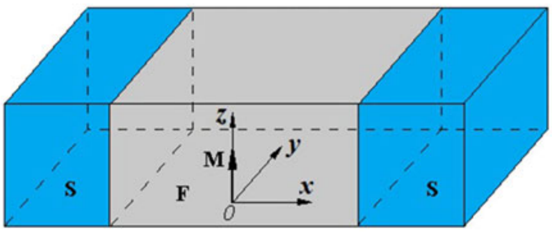

Fig. 1. Schematic of the φ_0–junction.

where φ is the phase difference between the superconductors across the junction, I is the external current, $E_s(\varphi, \varphi_0) = E_J[1 - \cos(\varphi - \varphi_0)]$, and $E_J = \Phi_0 I_c/2\pi$ is the Josephson energy. Here Φ_0 is the flux quantum, I_c is the critical current, $\varphi_0 = l\upsilon_{so} M_y/(\upsilon_F M_0)$, υ_F is Fermi velocity, $l = 4hL/\hbar\upsilon_F$, L is the length of F layer, h is the exchange field of the F layer, $E_M = -K\mathcal{V}M_z^2/(2M_0^2)$, the parameter υ_{so}/υ_F characterizes a relative strength of spin-orbit interaction, K is the anisotropic constant, and $\mathcal{V}$ is the volume of the F layer.

The magnetization dynamics is described by the Landau-Lifshitz-Gilbert equation [9], which can be written in the dimensionless form as follows:

$$\begin{aligned}\frac{dm_x}{dt} &= \frac{1}{1+\alpha^2}\big\{-m_y m_z + Grm_z \sin(\varphi - rm_y) \\ &\quad - \alpha\big[m_x m_z^2 + Grm_x m_y \sin(\varphi - rm_y)\big]\big\}, \\ \frac{dm_y}{dt} &= \frac{1}{1+\alpha^2}\big\{m_x m_z \\ &\quad - \alpha\big[m_y m_z^2 - Gr(m_z^2 + m_x^2)\sin(\varphi - rm_y)\big]\big\}, \\ \frac{dm_z}{dt} &= \frac{1}{1+\alpha^2}\big\{-Grm_x \sin(\varphi - rm_y) \\ &\quad - \alpha\big[Grm_y m_z \sin(\varphi - rm_y) - m_z(m_x^2 + m_y^2)\big]\big\}\end{aligned} \tag{2}$$

where α is a phenomenological Gilbert damping constant, $r = l\upsilon_{so}/\upsilon_F$, and $G = E_J/(K\mathcal{V})$. The $m_{x,y,z} = M_{x,y,z}/M_0$ satisfy the constraint $\sum_{\alpha=x,y,z} m_\alpha^2(t) = 1$. In this system of equations time is normalized to the inverse ferromagnetic resonance frequency $\omega_F = \gamma K/M_0 : (t \to t\omega_F)$, γ is the gyromagnetic ratio, and $M_0 = \|\mathbf{M}\|$.

The system of (2), together with the corresponding expression for the phase difference, specified for each considered effect of magnetization reversal, has been solved by using a fourth-order Runge–Kutta method. In what follows we obtain time dependence of the magnetization $m_{x,y,z}(t)$, phase difference $\varphi(t)$, and superconducting current $I_s(t) = \sin(\varphi(t) - rm_y(t))$. The superconducting current is normalized to the critical current.

III. Magnetization Reversal in φ_0 Junction By Current Pulse

In the present section, we investigate the magnetization reversal in the system described by (2) under the influence of the electric current pulse of rectangular form. The effect of rectangular electric current pulse are modeled by $I_{\text{pulse}} = A_s$ in the Δt time interval $(t_0 - \frac{\Delta t}{2}, t_0 + \frac{\Delta t}{2})$ and $I_{\text{pulse}} = 0$ in other

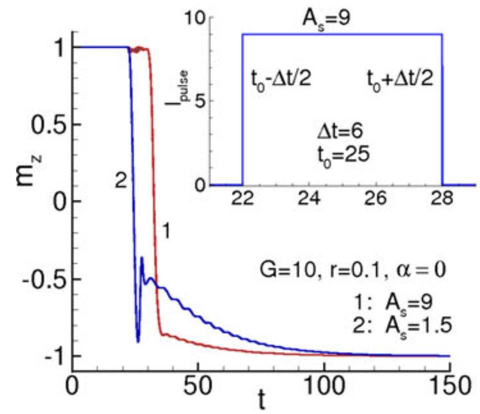

Fig. 2. Transition dynamics of the magnetization component m_z for a system with rectangular current pulse shown in the inset for two pulse amplitudes.

cases. The form of the current pulse is shown in the inset to the Fig. 2. Here we consider the JJ with low capacitance C ($R^2C/L_J << 1$, where L_J is the inductance of the JJ and R is its resistance), i.e., we do not take into account the displacement current. So, the dynamics of phase difference in this case can be described by

$$\frac{d\varphi}{dt} = \frac{1}{w}\left[I_{\text{pulse}} - \sin(\varphi - rm_y)\right] \tag{3}$$

where $w = \frac{V_F}{I_c R} = \frac{\omega_F}{\omega_R}$, $V_F = \frac{\hbar\omega_F}{2e}$, I_c - critical current, R- resistance of JJ, and $\omega_R = \frac{2eI_cR}{\hbar}$ - characteristic frequency. To describe the dynamics of the system, we have solved the system of (2) together with (3). Time dependence of the electric current is determined through time dependence of phase difference φ and magnetization components m_x, m_y, and m_z. It is found that the reversal of magnetic moment can indeed be realized at optimal values of JJ (G, r) and pulse (A_s, Δ, t_0) parameters [12].

The main part of Fig. 2 demonstrates the magnetization reversal under the influence of the electric current pulse, for the case without dissipation $\alpha = 0$ at two pulse amplitudes $A_s = 9$ and $A_s = 1.5$. We see a complete reversal in both the cases, but at $A_s = 9$ time needed for that is smaller. In case $A_s = 9$, we have observed the small oscillations of m_z when pulse is switched ON, and then sharp transition with continued small oscillations decreasing till the value $m_z = -1$. So, at small amplitude A_s we observe a sharp decrease of m_z immediately after the pulse is switched ON, then after a large enough peak, it limits to the value $m_z = -1$ demonstrating small oscillations. We stress that the transition dynamics and probability of the magnetization reversal of the investigated system depend crucially both on all the parameters of the Josephson junction as well as on current pulse ones. A relatively small change of the system parameters destroys the full magnetization reversal. Particularly, as demonstrated in Figs. 4 and 5, the magnetization reversal only occurs over a certain range of parameters. At the fixed values of the other parameters used in Figs. 4 and 5, full reversal only occurs when the dissipation parameter is smaller than $\alpha = 0.25$ (Fig. 4) or for the spin-orbit coupling constant in the interval $0.048 < r < 0.2$ (Fig. 5). By changing the other parameters, we have also observed full magnetization reversal over the different

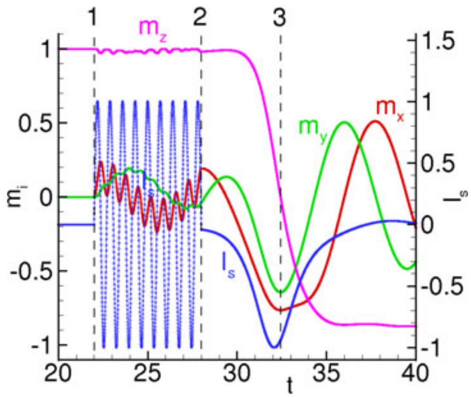

Fig. 3. Dynamics of the magnetization components m_x, m_y, m_z and superconducting current I_s at $A_s = 9$.

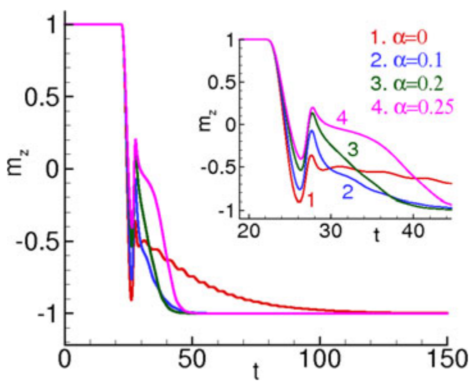

Fig. 4. Magnetization reversal at $A_s = 1.5$ and different values of the dissipation parameter. Other parameters are the same as in Fig. 2 Inset enlarges the transition region, numbers indicate the value of dissipation parameter.

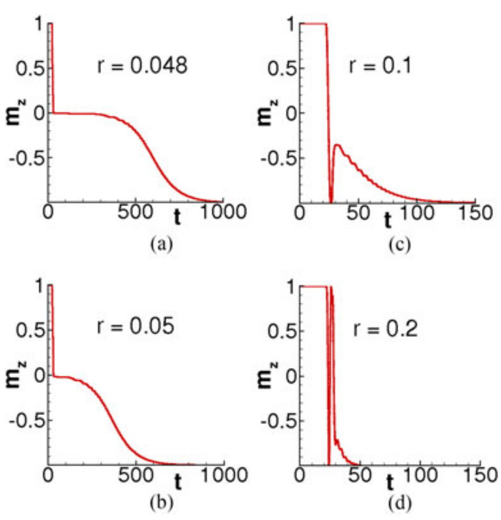

Fig. 5. Effect of spin-orbit coupling on magnetization parameters at $A_s = 1.4$, $G = 10$, and $\alpha = 0$.

intervals of α and r. We note that the system is very sensitive to the parameters of the external control, also demonstrating some intervals of pulse amplitude and pulsewidth at fixed other parameters of the model, which correspond to the magnetization reversal.

The dynamics of the magnetic moment components and superconducting current is illustrated in Fig. 3, at the same values of G, r, and α, that were used in Fig. 2, with the amplitude $A_s = 9$. We have identified three regions, as indicated by the dashed lines 1, 2, and 3 in the figure. For the time interval 1–2, i.e., during the pulse time, we see that the oscillations of superconducting current in response to the changing of the phase difference is 2π. When the current pulse is switched OFF (dashed line 2), the superconducting current at this moment has been decreased, which is the reason for the decreasing of m_y and m_x to the negative values shown, and the forcing of m_z to zero. We point out that, at the time corresponding to the minimum of m_y (dashed line 3), the component m_z equals to zero. The damped oscillations of m_y and m_x with a shifted phase leads to $m_z = -1$.

The effect of dissipation at another value of current pulse amplitude ($A_s = 1.5$), is demonstrated in Fig. 4. Here we see that there are no small oscillations of m_z, immediately after the pulse is switched ON, even at $\alpha = 0$. Instead there is a sharp decrease to the negative value, and then a relatively large peak with a size depending on the dissipation parameter. This peak occurs during the pulse interval. After the peak, we observe a transition to $m_z = -1$ in the interval that depends on the value of dissipation parameter, as shown in the inset. At small dissipations, the full magnetization reversal appears faster with increasing α.

Magnetization reversal at different values of spin-orbit coupling is demonstrated in Fig. 5. These calculations have been performed at current pulse amplitude $A_s = 1.4$ and intensity of spin-orbit coupling $G = 10$ for the case without dissipation ($\alpha = 0$). The reversal of magnetic moment is not observed at small r, until the value $r = 0.048$, when it demonstrates a transition over a long monotonic time interval, as shown in Fig. 5(a). This interval decreases with r [see Fig. 5(b)]. Then, as we see in Fig. 5(c) and (d), the character of the transition to complete magnetization reversal similar to the effect of dissipation.

IV. Magnetization Reversal in φ_0 Junction By Linearly Decreasing Bias Voltage

We now discuss the possibility of the magnetization reversal by the applied voltage. It was demonstrated in [13] that, the use of a specific time dependence of the bias voltage, applied to the weak link, leads to the reversal of the magnetic moment of the nanomagnet. Cai and Chudnovsky demonstrated the reversal of the nanomagnet by linearly decreasing bias voltage $V = 1.5 - 0.00075t$ (see [13], Fig. 3). The magnetization reversal, in this case, was accompanied by a complex dynamical behavior of the phase and continued during a sufficiently long time interval. Here we demonstrate a similar mechanism of the magnetization reversal in φ_0–junction. When the voltage in the φ_0–junction is applied, Josephson oscillations appear. In normalized units, the expression for the phase difference can be written as follows:

$$\varphi = (\omega_J - \gamma t)t \tag{4}$$

where ω_J is the Josephson frequency and γ is constant.

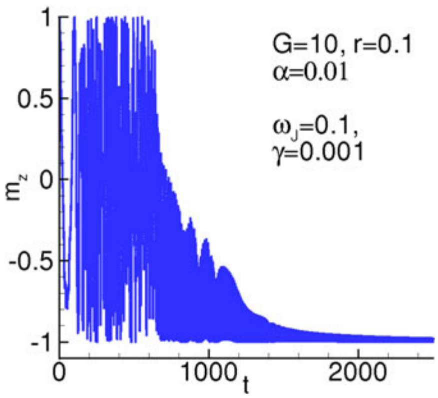

Fig. 6. Magnetization reversal by linearly decreasing bias voltage for $\omega_J = 0.1$, $\gamma = 0.001$ and model parameters $G = 10$, $r = 0.1$, and $\alpha = 0.01$.

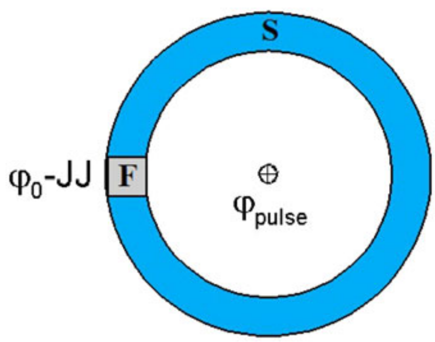

Fig. 7. Schematic of the rf-SQUID, containing the φ_0–junction.

Fig. 6 shows an example of the m_z time dependence, calculated from the Landau-Lifshitz-Gilbert (2) and the expression (4). We see a rather complex unstable oscillatory behavior in m_z, over the range of ± 1 and in time interval [0,650]. Thereafter, the amplitude of m_z decreases slowly until full magnetization reversal occurs. We note that in [13] the magnetization reversal by this specific time dependence of the bias voltage, applied to the weak link, is explained as a result of the effective field decreasing in the course of the reversal. In this case the ac field generated by the oscillating tunneling current continuously pumps spin excitations into the nanomagnet. This leads to the full reversal of the magnetic moment. Probably, a similar mechanism also occurs in our case. A more detailed study of this effect will be done elsewhere.

V. Magnetization Reversal in rf-SQUID With φ_0 Junction by the Pulse of External Magnetic Field

Finally, we discuss the possibility of the complete magnetization reversal by the pulse of the external magnetic field in a system consisting of an rf-SQUID with a φ_0–junction. The scheme of the system is shown in Fig. 7.

In order to describe the dynamics of the rf-SQUID [14], we write the expression for total flux trough the system as

$$\Phi = \Phi_{\text{pulse}} - LI \tag{5}$$

where Φ_{pulse} is the flux created by the external magnetic field pulse, L is the inductance of the superconducting loop, and I is the current through φ_0-junction. In the case of standard rf–SQUID, the total magnetic flux leads to the creation of the phase difference in the junction, which is determined as $\varphi = 2\pi\Phi/\Phi_0$, where $\Phi_0 = h/(2e)$ is the flux quanta. Taking into account the phase difference shift rm_y in the φ_0-junction, we rewrite the expression of the phase difference created by the magnetic flux as

$$\varphi - rm_y = 2\pi\Phi/\Phi_0. \tag{6}$$

The current through the junction in the framework of the resistivity shunted junction (the overdamped case) can be written as

$$I = \frac{\hbar}{2eR}\frac{d\varphi}{dt} + I_c \sin(\varphi - rm_y) \tag{7}$$

where R is the resistance of the junction. Using expressions (5), (6), and (7), we can write the equation for the phase difference of rf-SQUID with the φ_0-junction in normalized variables as

$$\frac{d\varphi}{dt} = \frac{1}{w}\left[\frac{\varphi_{\text{pulse}} - \varphi + rm_y}{L} - \sin(\varphi - rm_y)\right] \tag{8}$$

where L is normalized to the $L_0 = 2\pi I_c/\Phi_0$. We have taken a pulse of external magnetic field φ_{pulse} in the rectangular form. It is equal to φ_A in time interval $t_0 \pm dt$ and to zero out of this interval. The form of the magnetic field pulse is shown in the inset of the Fig. 8.

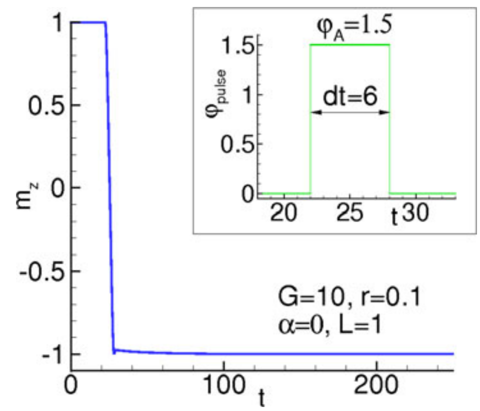

Fig. 8. Magnetization reversal in rf-SQUID with the external magnetic field pulse demonstrated in the inset.

An example of the calculated time dependence of the m_z is shown in Fig. 8. Calculations are performed with pulse characterized by time interval $dt = 6$ and amplitude $\varphi_A = 1.5$. We see the full magnetization reversal in φ_s junction under the external magnetic field pulse. After the pulse switching OFF, the m_z tends to -1 with small oscillations. In order to explain the character of changing m_z and the origin of its small oscillations after the pulse switching OFF, we have analyzed the dynamics of components of magnetization m_x and m_y, which are shown in Fig. 9.

As we see, during the pulse of the external field, the superconducting current is increased. After the pulse is switched OFF, it decreases, causing the oscillations of magnetization component m_x and m_y. Their oscillation phase is shifted. We note that the presence of the oscillations in m_x and m_y, is related

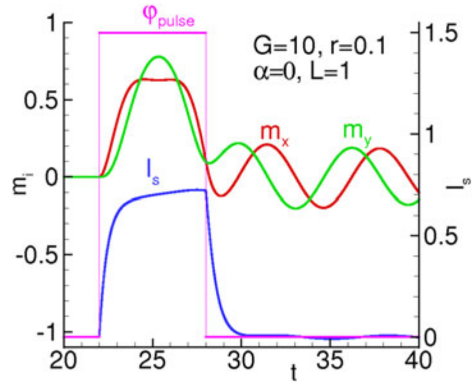

Fig. 9. Dynamics of m_x m_y and superconducting current I_s in rf-SQUID under the external magnetic field pulse.

to the small oscillation of m_z. The origin of the small oscillation of the superconducting current is related to the fact that, after the switching of the pulse, the net is locked to the internal resistance. The manipulation of the magnetic properties of the φ_0-junction in the rf-SQUID opens an attractive possibility for the applications in superconducting spintronics and electronics.

VI. Conclusion

We studied magnetization reversal in superconductor-ferromagnet-superconductor φ_0-Josephson junctions, with direct coupling between the magnetic moment and Josephson current. Three types of effects, leading to magnetization reversal of ferromagnetic layer were demonstrated, including the magnetic moment reversal by pulse of superconducting current, by linearly decreasing bias voltage in φ_0-junction, and, for the first time, by a pulse of the external magnetic field in the rf-SQUID with a φ_0-junction. The influence of variations in the model parameters on the magnetization reversal was investigated in some detail. We consider that the observed features may find an applications in different fields of superconducting spintronics.

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